PERFORMANCE TRADE-OFFS: INTERSUBBAND vs. INTERBAND QUANTUM CASCADE LASERS



International Workshop on Quantum Cascade Lasers (Sevilla, 5 January 2004)

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With devices from:

Manijeh Razeghi & Steve Slivken (Northwestern U.)

Embedded Talk:

PROGRESS & CHALLENGES IN THE DEVELOPMENT
OF INTERBAND CASCADE LASERS

R. Q. Yang & C. J. Hill *(JPL)*

Question: Which most promising for high cw powers in mid-IR (3-5 μm)?

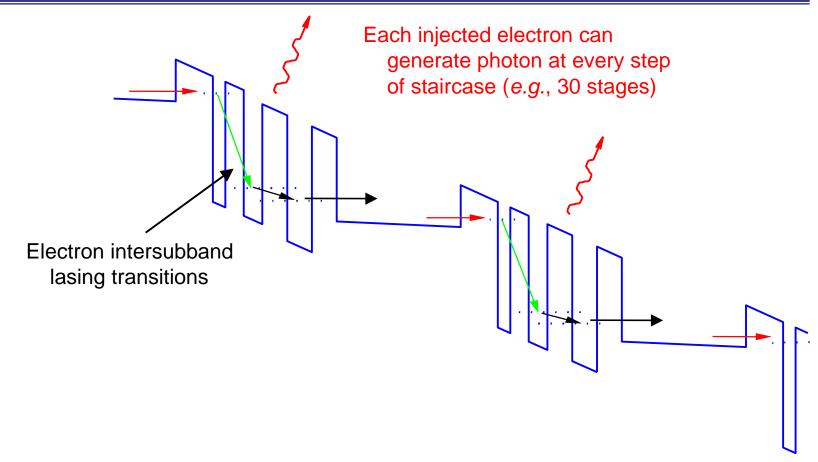
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QUANTUM CASCADE LASER (QCL)

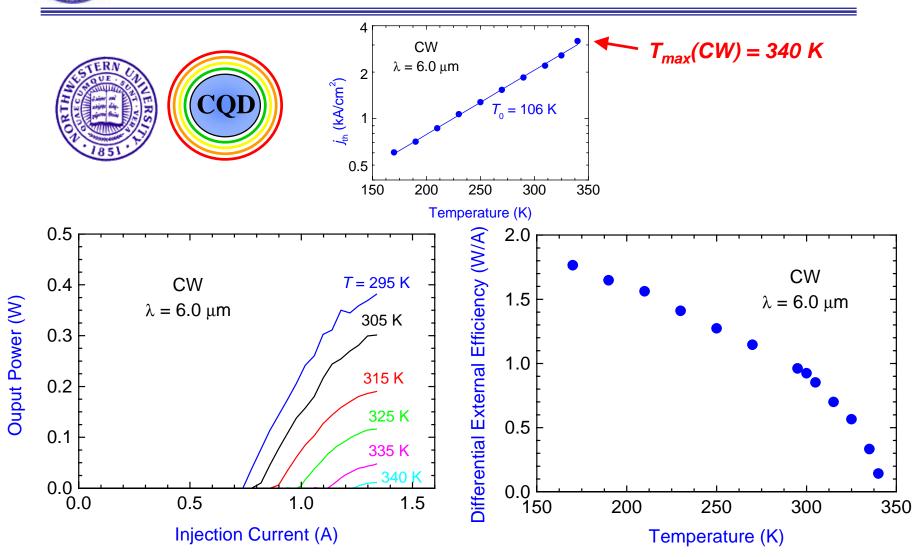


- Advantages: Multiple stages for high slope efficiency, Small threshold carrier density, Large T_0 , Mature materials (InP/GaAs), Low LEF
- Disadvantages: Multiple stages require greater heat dissipation, Short phonon lifetime increases threshold, Strain compensation required to reach λ < 5 μ m



NRL CHARACTERIZATION OF NORTHWESTERN

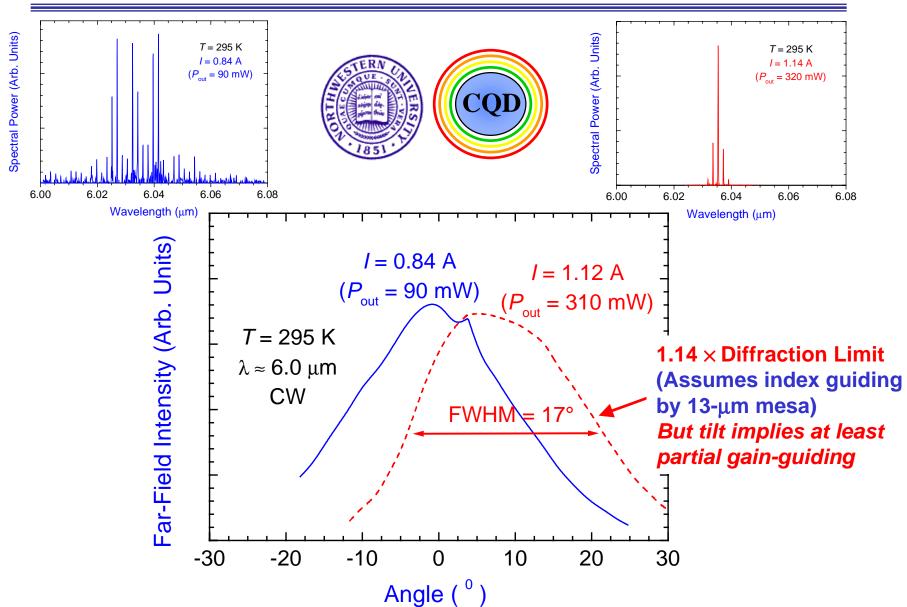
QCLs (Devices courtesy of M. Razeghi & S. Slivken)



CW P_{out} = 360 mW @ 300 K, 110 mW @ 325 K, η_{wall} = 2.7% @ 300 K

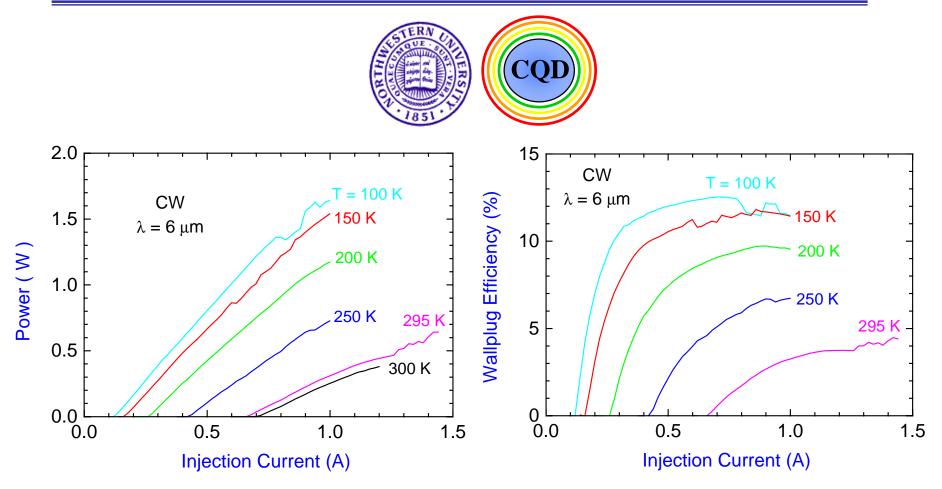


SPECTRA & FAR-FIELD





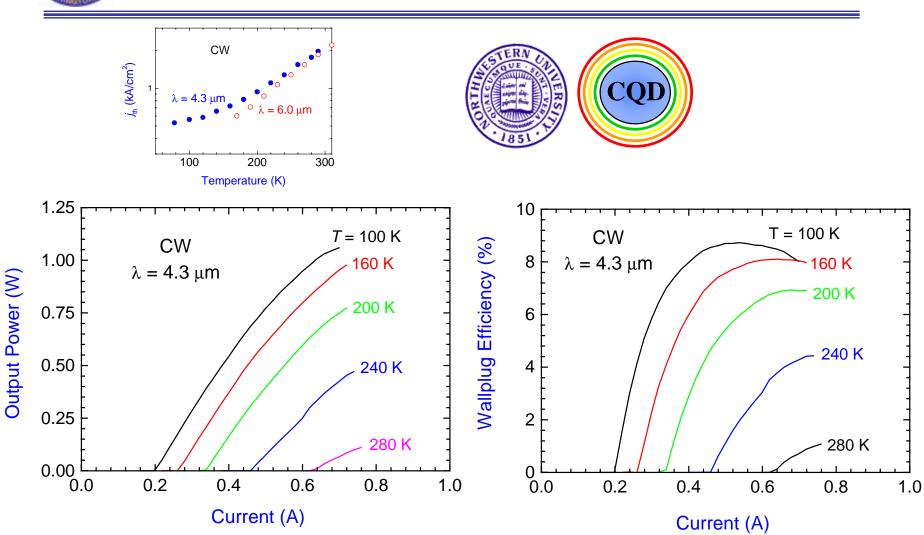
NEW 6 μm LASER



 $CWP_{out} > 1.1 \ W @ 200 \ K, 640 \ mW @ 295 \ K, \eta_{wall}(295K) = 4.5\%$



SHORTEN WAVELENGTH TO 4.3 μ m

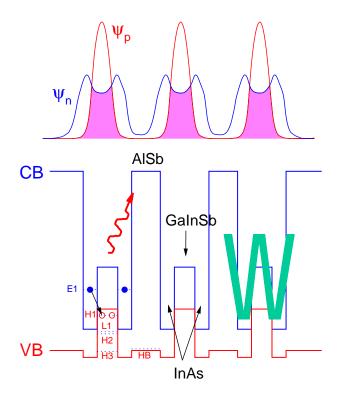


CW @ 160 K: $P_{out} \approx 1$ W, $\eta_{wall} = 8.1\%$



TYPE-II ANTIMONIDE "W" LASER

Meyer et al. APL 67, 757 (1995); U.S. Patent #5,793,787

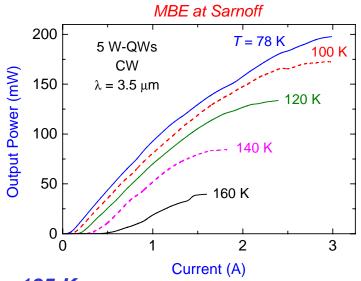


Advantages:

- Vs. type-I diodes: High differential gain, excellent electrical confinement, Auger suppression
- Vs. QCL: Interband relaxation for lower j_{th}, Single stage for lower heat-dissipation threshold

Disadvantages:

 Lower slope efficiency, Immature GaSb-based materials, Far less optimized

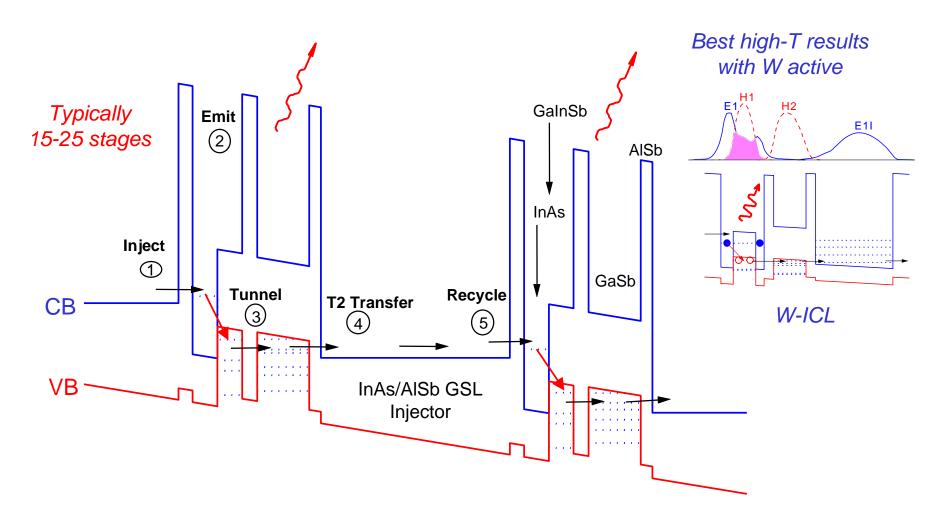


 $cw T_{max} = 195 K$ $\eta_{wall} = 7.2\% @ 78 K, 5.4\% @ 140 K$



INTERBAND CASCADE LASER (ICL)

First proposed: R. Q. Yang, Superlatt. Microstruct. 17, 77 (1995)



Advantages: High slope efficiency (Multiple stages), Lower threshold (long τ_R) Disadvantages: Higher heat-dissipation threshold (Multiple stages), GaSb-based





Progress and Challenges in the Development of Interband Cascade Lasers

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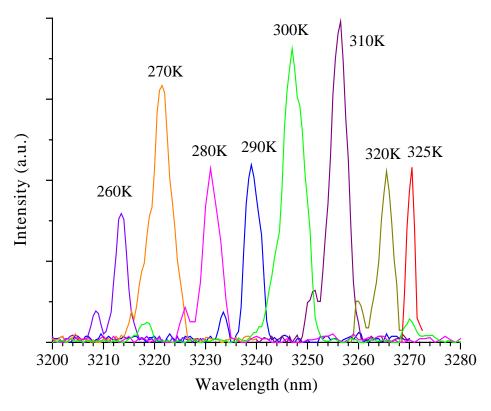
International Workshop on Quantum Cascade Lasers Seville, Spain, Jan. 4-8, 2004



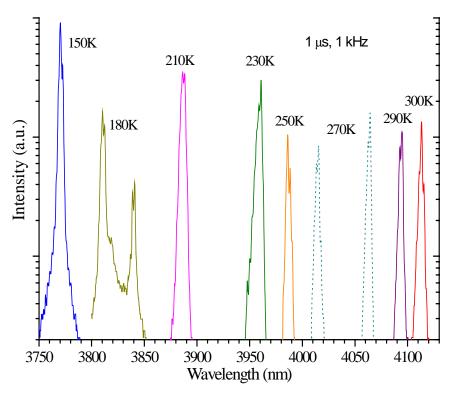
HIGHER-TEMPERATURE OPERATION







23-stages, 150-μm x 1-mm mesa



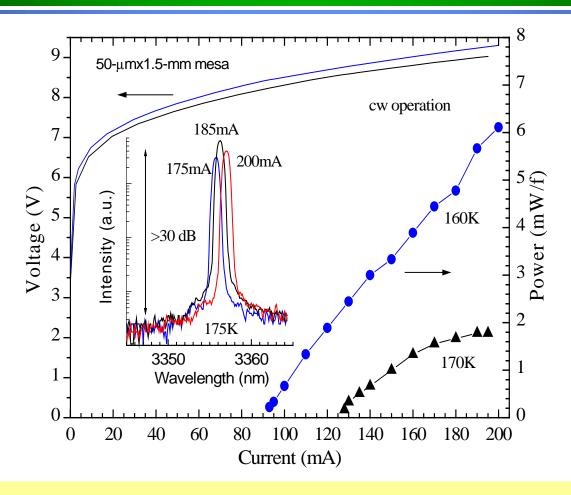
Pulsed lasing at λ = 3.27 μ m up to 325 K (Limited by circuit ringing & temperature setting of cryostat)

Longest-wavelength III-V interband diode laser operating at room temperature ($\lambda = 4.1 \mu m$)



DFB IC LASERS





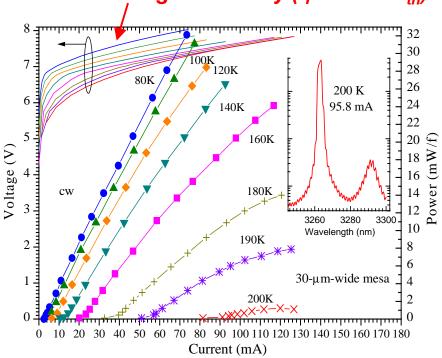
- DFB lasers operated cw up to 175 K in single mode (> 30 dB sidemode suppression)
- Wavelength tunable with current at a rate of ~0.05 nm/mA
- Temperature tuning coefficient ~0.2 nm/K
- Output power (>1 mW) at 175 K enough for gas sensing

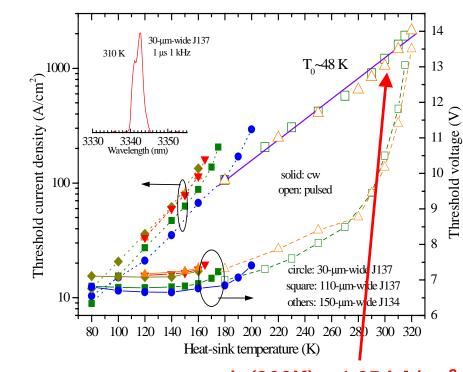


LOW THRESHOLD, HIGH CW T_{max}









 $J_{\rm th}$ (200K in cw) ~304 A/cm² (30- μ m-wide device) $R_{\rm sth}$ ~ 14 K·cm²/kW (specific thermal resistance)

 $j_{th}(300K) = 1.05 \text{ kA/cm}^2$ (Lower than any QCL)

If $R_{\rm sth}$ reduced to 2 K·cm²/kW (smaller device size & better package): theoretical cw $T_{\rm max} \ge 285$ K

Related Maxion results:

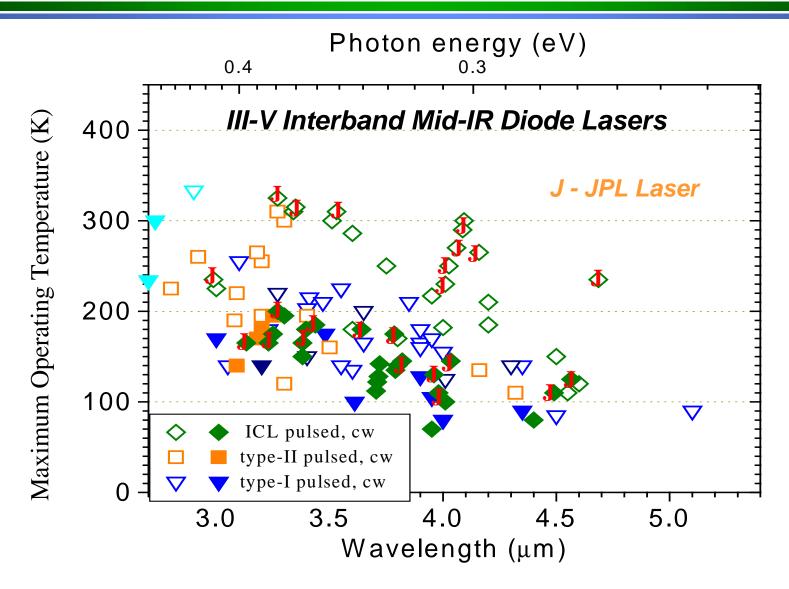
At 80 K: $\eta_{wall} = 23\%$, DEQE ≈ 1 W/A (532%)

 $cw T_{max} = 214 K$



JPL ICL STATUS: T_{max} (Compared to literature data, as of 9/2003)







HEAT DISSIPATION REQUIREMENTS AT 300 K

(QCL vs. W-ICL vs. W-Diode)

Current best:

- QCL: Current best cw threshold is $j_{th} \approx 1.9 \text{ kA/cm}^2$ (pulsed 1.2 kA/cm² reported), bias (N = 30 stages) is $V_{th} \approx 9 \text{ V}$ Means $I_{dis} \approx 17 \text{ kW/cm}^2$ must be dissipated
- ICL: Best reported pulsed is $j_{th} \approx 1.05 \text{ kA/cm}^2$ at $V_{th} = 10.2 \text{ V}$ (N = 15) Means $I_{dis} \approx 11 \text{ kW/cm}^2$
- W-Diode: For only pulsed 300 K result to date ($N_{\rm QW} = 10$), $j_{\rm th} \approx 16$ kA/cm² at $V_{\rm th} \approx 1.2$ V Means $I_{\rm dis} \approx 19$ kW/cm²

Scaling:

- QCL: j_{th} scales with loss; V_{th} scales with N
- ICL: j_{th} scales with Auger lifetime (τ_A) , depends on loss; V_{th} scales with N
- W-Diode: j_{th} scales with N_{QW} & τ_A , depends on loss; Single-stage $V_{th} \approx \eta \omega$

Headroom:

- QCL: How much further decrease of loss?; Decrease N to decrease V_{th} ? (So far, j_{th} then increases) [$I_{dis} \approx 8-10 \text{ kW/cm}^2$ probable More?]
- ICL (15-25 stages): Much less mature so probably more headroom Optimize V_{th} & possibly τ_A [$I_{dis} \approx 5$ -6 kW/cm² probable More?]
- W-Diode: Very immature, so considerable headroom; $V_{th} \approx 0.5 \text{ V}$; Loss optimization may allow $N_{QW} = 3-5$ [$I_{dis} \approx 5 \text{ kW/cm}^2$ probable More?]
- Hybrid W-ICL with 3-5 stages (only enough to overcome loss): Combines higher gain of ICL with lower V_{th} (≈ 1.5 -2.5 V) of W-Diode [Expect $I_{dis} < 3 \text{ kW/cm}^2$]



HIGH POWER: WHAT ABOUT ABOVE jth?

Jutput Power (W)

dp/di

Current (A)

High-power laser must reach & exceed threshold, maintain large slope, minimize droop

- Heat sinking: InP overgrowth favors QCL, but gold plating may neutralize (Maxion ICL reports lowest $R_{\rm sp}$)
- Higher T_0 of QCL: Slower performance degradation for given ΔT
- Slope efficiency depends on loss & number of stages (N)
 - Loss: Thus far, lower in QCL (≈ 10 cm⁻¹ $vs. \ge 20$ cm⁻¹)
 - Advantage likely to persist because: (1) Fewer carriers, (2) No holes
 - Slope efficiency: Thus far, higher in QCL (e.g., 1 W/A for NU QCL @ 300 K vs. 0.42 W/A for Maxion ICL @ 200 K) Immature ICL will improve
- Broaden stripe: Probably a necessity when scaling power up to ≥ 10 W range
 - Precludes lateral heat flow, so low I_{dis} even more critical
 - Broad-stripe QCL (lower LEF) should maintain better beam quality
 - Photonic-Crystal DFB approach may improve both QCLs & ICLs



OTHER CONSIDERATIONS

- Manufacturability: InP-based materials growth/processing (QCLs) far more mature than GaSb-based (ICLs)
- Wavelength coverage (Apples to oranges?): Above analysis compares QCLs emitting at $\lambda \approx 6 \mu m$ to ICLs emitting at $\lambda \approx 3.5 \mu m$
 - Both get worse as they move toward the middle Advantages will shift!
 - One likely outcome: QCLs will be advantageous at $\lambda > \lambda_{Cross}$ while ICLs advantageous at $\lambda < \lambda_{Cross}$ Value of λ_{Cross} remains to be determined
- Advantage also shifts with temperature: Scenarios where QCLs are favored at T≥ 300 K may shift to ICLs with TE-cooling (e.g., 240 K)
 - ICL in low-T limit: $j_{th} = 9 \text{ A/cm}^2$



CONCLUSIONS

- Dramatic recent progress by both QCLs & ICLs
- High-power 3-5 μm CW lasing with electrical pumping at ambient (or TE-cooler) temperature seems increasingly likely
- ICL (or especially "hybrid" ICL) projected to require less power dissipation, but QCL has other advantages
- Jury still out on which will ultimately dominate under given $\lambda \& T$ constraints (Where is λ_{Cross} ?)

